OPERATIONAL PROPERTIES OF DLC COATINGS AND THEIR POTENTIAL APPLICATION

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Abstract

Diamond-like carbon (DLC) coatings are currently used in many areas of the economy. Due to their unique properties, such as high hardness, low friction, and high wear resistance, are also used in industry, especially on machine parts exposed to increased wear. The paper presents the results of operational tests of diamond-like carbon coatings deposited in the physical vapor deposition (PVD) process on samples made of 4H13 stainless steel. The properties of DLC coatings were assessed based on microstructure analysis, nanohardness and roughness measurements, and tribological tests. The results obtained during the tests showed that using diamond-like coatings significantly improves the tribological properties. In addition, the coatings are free of pores and microcracks. In addition, DLC layers are characterized by high nanohardness and low roughness. This type of coating can be used on surfaces of machine parts.

Keywords: Diamond-like carbon, PVD, coatings, properties

1. INTRODUCTION

DLC coatings are a metastable form of amorphous carbon, composed of sp^2 hybridized bonds found in graphite and sp^3 bonds found in a diamond. Depending on the proportion of these bonds, DLC exhibits different tribological properties. The hardest and most durable mixture is amorphous tetrahedral carbon (ta-C) (the content of sp^3 bonds - approx. 70%). Coating with a ta-C layer with a thickness of 2 μm increases the resistance of stainless steel to abrasive wear, increasing its life cycle up to 85 years [1]. Due to their carbon content, the DLC coatings themselves do not show high resistance to high temperatures. To improve their thermal stability, admixtures of non-metals (e.g. hydrogen, boron, nitrogen, phosphorus, fluorine, and sulfur) or metals (copper, nickel, tungsten, titanium, molybdenum, silicon, chromium, and niobium) are used. It can be concluded that DLC coatings can be used wherever necessary to reduce the coefficient of friction and the intensity of wear of parts. DLC coatings are applied to the surface of injection molds, and the electrical properties and biocompatibility cause a growing interest in using these coatings in medicine. This also improves operational features of coatings operating in corrosive [2, 3] and biocorrosive aggressive environments [4,5].

In industry, DLC coatings cover machine parts such as bearings, cylinders, pistons, gears, or mechanical seals [6,7]. They are also applied to the surface of cutting tools, injection molds, and various tribological pairs [8]. In consumer products, they can be found, among other things, on the surfaces of wristwatches (including bracelets and protective glass) or needles [9]. DLC coatings can also be applied to the surfaces of precision mechanical systems such as modern fuel injectors for compression ignition engines [10]. Applying diamond-like coatings to military equipment (e.g. firearm barrels) is particularly interesting [11].

The unique features of DLC coatings have a significant impact on quality improvement in production processes [12,13] and during operation, which also affects the quality management systems themselves [14,15]. The research on the properties of surfaces modified by DLC also inspires experimental study [16,17] and data analysis methodology [18,19], including non-parametric models [20]. In recent years, analyses of stochastic series [21] and stochastic fields [22,23] have been intensively implemented in surface layer studies, combined with numerical experiments [24,25].

One of the companies that use the unique properties of DLC coatings is ISKRA ZMILS Sp. z o.o. located in Kielce, Poland. DLC coatings are used for (**Figure 1**):

- surface coating of RPK 1032V rollers – used in wire straightening units. They are single-row ball bearings with a thickened outer ring with a V-groove covered with DLC on its surface,
- covering the working surfaces of rod end bearing – such elements are used for technical devices which perform pendular movements, among others, in light industry, food industry, or transport.

a) b)

Figure 1 Machine parts with DLC coatings manufactured by ISKRA ZMILS Sp. z o.o.:
a) RPK 1032V roller, b) Rod end bearing

2. MATERIALS AND METHODS

Materials with anti-wear functions for friction nodes coated with diamond-like coatings (DLC) of a-C:H type with W and Cr interlayer, deposited by physical vapor deposition PVD process, were selected for this study. The choice of DLC coatings was dictated by their excellent properties and the possibility of extensive application in various industries. The amorphous hydrogenated carbon (a-C:H) layer, also called carbon-like coating, is characterized by high mechanical properties.

Stainless steel 4H13 was used as the substrate material. The chemical composition of the steel used was as follows (wt %): C: 0.36-0.45; Mn: 0.50-0.80; Cr: 12.0-14.0; Si: 0.60-0.80; Mo: 0.5-0.7; V: 0.2- 0.3; Ni: 0.1-0.60; P: max 0.04, S: max 0.03, other is Fe.

PVD thin anti-wear coating processes occur at elevated temperatures, resulting in the tempering of the surface layers and reduced hardness. DLC coatings were obtained at the following processes and temperatures:

- a-C:H by physical vapor phase PVD sputter deposition at <300 °C,
- 350°C substrate material temperature.

3. RESULTS AND DISCUSSION

The microstructure analysis of DLC coatings was performed using a JEOL JSM-7100F field emission scanning electron microscope. **Figure 2** shows the microstructure of the DLC coating. The thickness of the layer was about 3 µm. The microstructure analysis shows that the coating is free of pores and microcracks. Moreover, the boundary line between the coating and the substrate is visible.

The elemental distributions on the cross-section in the amorphous hydrogenated carbon layer on the tested stainless steel surface are shown in (**Figure 3**). It is observed that the elemental distributions of Fe, Cr, W, and C are clearly visible on the diamond-like layers. In addition, all element distributions are heterogeneous, and some grains are oxygen deficient.

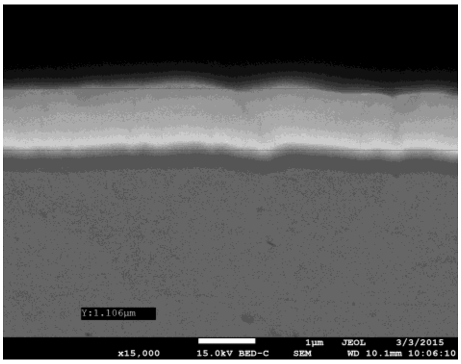

Figure 2 Microstructure of DLC coating

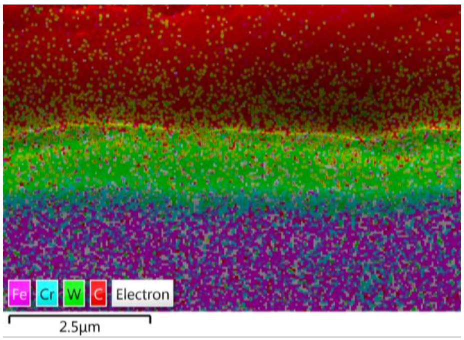

Figure 3 Elements distribution in the specimen with DLC coating

Producing coatings with the required micromechanical properties is a significant research challenge. In the manufacturing process, it is necessary to define the controlled parameters and properties expected from the resulting coating. The multitude of controlled parameters and their values result in many combinations resulting in high costs. The nanoindentation and Young's modulus measurements were performed using a nanoindentation tester made by NANOVEA company, located in the Physics Laboratory of Silesian University of Technology, Poland. The tests were carried out under the following parameters: linear load, max. load 3.2 mN, load and unload rate 40 mN/min, and load/unload cycle interval 3 s. The average values of nanohardness and Young's modulus were determined from 10 measurements. The nanohardness was determined as the depth of penetration of the indenter, while the slope of the unloading curve determined the longitudinal modulus. **Table 1** shows the average values of nanohardness and Young's modulus along with the standard error.

Analyzing **Table 1**, it can be seen that the nanohardness of the DLC coating was about 26% higher compared to the nanohardness of the 4H13 stainless steel. A similar analogy can be observed by analyzing Young's modulus values for the DLC coating and 4H13 stainless steel.

Table 1 Nanohardness and modulus of elasticity values with standard error

Material	Nanohardness (GPa)	Young’s modulus (GPa)
DLC coating	7.55 ± 0.10	92.87 ± 2.05
4H13 stainless steel	5.60 ± 0.40	44.00 ± 4.30

Friction resistance tests (technically dry friction) were carried out on a T-01M tribological tester in a ball-ring association. As samples, 4H13 stainless steel rings with DLC coatings were used. The counter-sample was a 6.3 mm diameter ball made of 100Cr6 steel.

Tests on the tester were conducted at the following friction parameters:

- linear velocity v= 0.8 m/s,
- test time t = 3600 s,
- load range Q = 4.9 N; 9.8 N; 14.7 N.

The sample graph (**Figure 4**) shows the coefficient of friction and linear wear as a function of time for a load of 4.9 N.

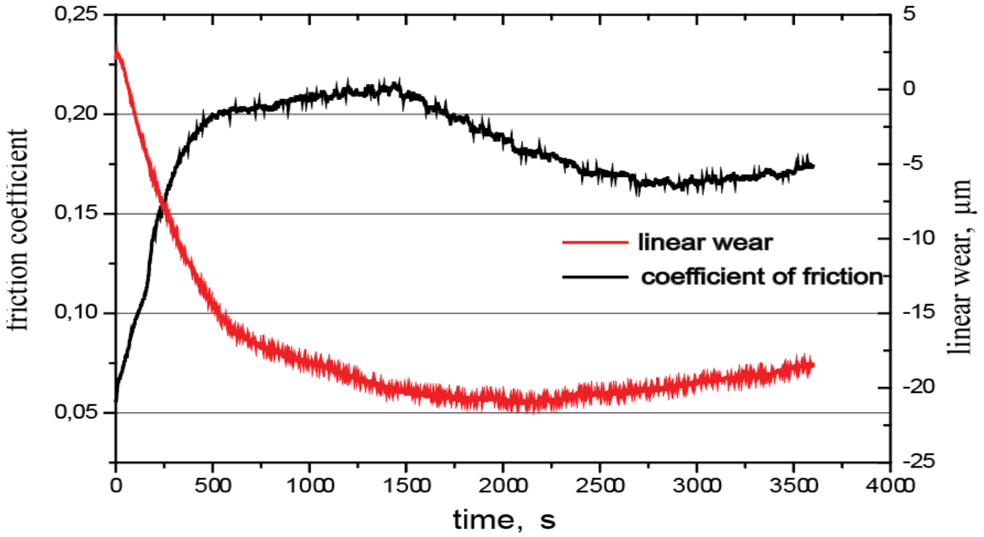

Figure 4 Line graph of wear as a function of time for a load of 4.9 N

The transformation of the technological surface layer into the operational surface layer occurred during the technically dry friction of the investigated coatings. This effect took place mainly due to pressure and sliding velocity and the influence of the ambient atmosphere close to the tested surface. Stabilization of the state of the wear-protective surface layer was observed.

It can be seen in (**Figure 4**) that the stabilization of the friction factor occurs after about 2700 seconds, and its value oscillates from 0.16 to 0.18. The course of linear wear is exponential.

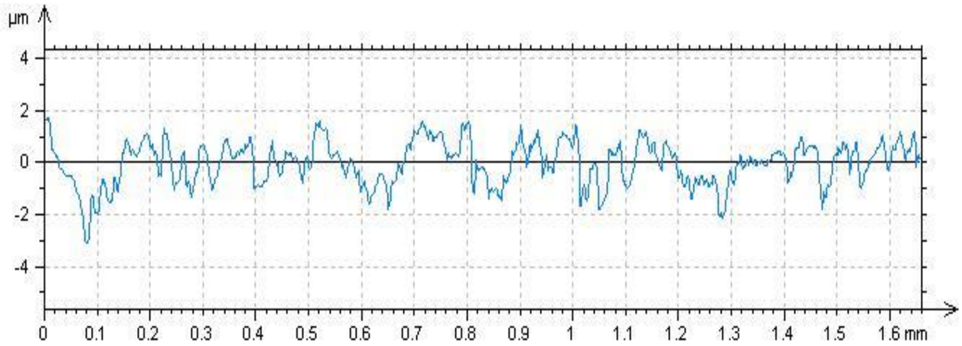

Figure 5 Roughness profile of the DLC coating

The surface roughness measurements were carried out in the Laboratory of Computer Measurements of Geometric Values of the Kielce University of Technology. The tests were carried out using the method of coherent correlation interferometry, allowing measurements with resolution in the z-axis up to 10 pm. The roughness was measured in two perpendicular directions. The average value was then calculated, which was Ra = 0.60÷0.66 µm. The 4H13 stainless steel samples had roughness ranging from 0.41 to 0.43 µm.

Table 2 Roughness profile parameters of the DLC coating

Roughness parameters	DLC coating
Rp (μm)	1.81
Rv (μm)	2.33
Rz (μm)	4.14
Rc (μm)	1.91
Rt (μm)	4.86
Ra (μm)	0.66
Rq (μm)	0.81

Figure 5 shows an example of a two-dimensional measurement of the surface microgeometry of a DLC coating. **Table 2** shows the most crucial average roughness parameters of the obtained surface layer. Low values of roughness parameters of the DLC coating also affect its mechanical properties.

4. CONCLUSIONS

Based on the study, the following conclusions can be formulated:

- DLC coatings had a homogeneous structure and were free of defects,
- the thickness of the layer applied with the PVD method was about 3 μm,
- the average value of the friction coefficient (at the moment of stabilization) obtained during tribological tests for the DLC surface layer was within the range of 0.16÷0.18,
- the layers of amorphous hydrogenated carbon had low roughness and high nanohardness,
- further studies will be directed to determine DLC coatings' corrosion and erosion resistance.

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